(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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(54) Title: METHOD AND SYSTEM FOR PRODUCING A HIGHER QUALITY ELECTROMYOGRAPHIC SIGNAL FROM AN ELECTRODE ARRAY
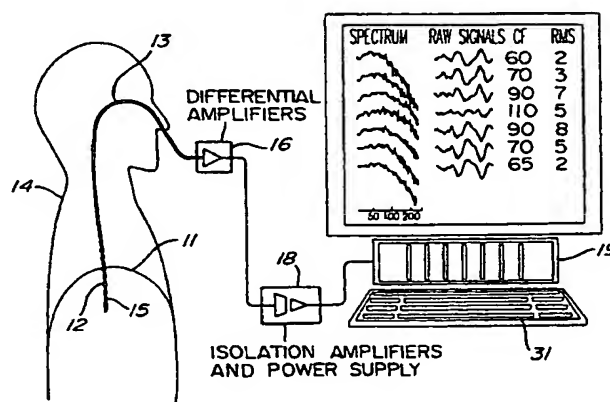
(57) Abstract: In a method and system for producing a higher quality electromyographic signal describing myoelectrical activity of an electrically active region of a subject's muscle, a plurality of EMG signals representative of the electrical activity of the electrically active region of the subject's muscle are sensed through an array of electrodes. A weighting function is applied to the detected EMG signals to thereby produce weighted signals, this weighting function containing correction features for the relative locations of the center of the electrically active region and the electrodes. Finally, a sum or mean of a feature of the weighted signals is calculated to thereby produce the higher quality electromyographic signal. Prior to calculating the sum or mean of the weighted signals, electromyographic quality of the weighted signals is evaluated, and the weighted signals or sum or mean of the weighted signals whose evaluated quality is insufficient are replaced. Alternatively, the higher quality electromyographic signal is replaced in response to weighted signals of insufficient quality. The method and system can also be used to determine signal strength or frequency contents of a signal falling outside the array of electrodes.

WO 01/03579 A1

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METHOD AND SYSTEM FOR PRODUCING A HIGHER QUALITY

ELECTROMYOGRAPHIC SIGNAL FROM AN ELECTRODE ARRAY

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BACKGROUND OF THE INVENTION

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1. Field of the invention:

The present invention relates to a method and system for producing a higher quality electromyographic signal from signals obtained with an array

15 of electrodes, in which the electrode-sensed signals are corrected through implementation of a weighting function.

2. Brief description of the prior art:

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The physiological mechanisms which generate myoelectrical activity when a muscle contracts have been known and understood for long time. In particular, how to record electromyographic signals from muscles through an array of electrodes is a well theoretically described topic in physiology.

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Although the theoretical understanding is impressive, the bio-physiological application of this theory is, in practice, still partly deficient. As of today, there is known only one standardized and automatic processing system taking into consideration factors such as electrode filtering due to

30 changes in the position of the array of electrodes relative to the center of the electrically active region of the muscle. Application of this technique includes

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limitations as to its adaptability to changes in inter-electrode distance and does not optimize the use of signals available along the electrode array with varying anatomy and inter-electrode distance.

5   Also, the prior art technology fails to provide for full correction of the signals obtained from electrodes of the array that are not symmetrically positioned with respect to the center of the electrically active region of the muscle.

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OBJECTS OF THE INVENTION

An object of the present invention is therefore to overcome
15   the above described drawback of the prior art by processing the electrode-sensed signals through a weighting function whose purpose is to correct these electrode-sensed signals for a distance separating the electrodes from the electrically active region of the muscle.

20   Another object of the present invention is to predict signals which cannot be measured through the array of electrodes.

SUMMARY OF THE INVENTION
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More particularly, in accordance with the present invention, there is provided a method of producing a higher quality electromyographic signal describing myoelectrical activity of an electrically active region of a
30   subject's muscle, comprising sensing through an array of electrodes a plurality of EMG (electromyogram) signals representative of the myoelectrical

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activity of the electrically active region of the subject's muscle, applying a weighting function to the detected EMG signals and thereby producing weighted signals wherein the weighting function contains correction features for the relative locations of the electrically active region and the electrodes,

5   and combining the weighted signals and thereby producing the higher quality electromyographic signal.

The present invention further relates to a system for producing a higher quality electromyographic signal describing myoelectrical

10 activity of an electrically active region of a subject's muscle, comprising an array of electrodes for sensing a plurality of EMG signals representative of the myoelectrical activity of the electrically active region of the subject's muscle, a weighting filter applied to the detected EMG signals to produce weighted signals wherein the weighting filter contains correction features for the relative

15 locations of the electrically active region and the electrodes, and a combiner of the weighted signals wherein the combined weighted signals constitute the higher quality electromyographic signal.

In accordance with preferred embodiments of the present

20 invention:

- the electrically active region of the subject's muscle comprises a center, the electrodes are separated from the center of the electrically active region by respective distances, the electrodes are separated

25 from each other by an inter-electrode distance, and the weighting function comprises correction features for:

— the relative location of the center of the electrically active region and the electrodes;

— the distance separating the center of the electrically active region and the electrodes;

30 — the size of the electrically active region; and

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—   the inter-electrode distance;

- the weighting function comprises correction features for both cancellation and distance damping effects;

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- the electrically active region of the subject's muscle comprises a center, the array of electrodes comprises a series of electrodes with an inter-electrode distance, each EMG signal is detected through at least two electrodes of the array, and applying the weighting function

10   comprises:

detecting the position of the center of the electrically active region about the array of electrodes;

relating the weighting function to the position of the center of the electrically active region with respect to the

15   electrodes of the series;

weighting each EMG signal by means of the weighting function related to the position of the center of the electrically active region with respect to the electrodes of the series;

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- the series of electrodes has a center and, when the center of the electrically active region is offset with respect to the center of the series of electrodes:

a larger number of EMG signals are detected by the

25   electrodes on one side of the center of the electrically active region than on the other side of that center of the electrically active region so that EMG signals are missing on the above mentioned other side; and

weigthing of the EMG signals comprises replacing the

30   missing EMG signals on the said other side by

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corresponding EMG signals from the said one side, and subsequently weighting the replacement EMG signals;

- combining the weighted signals comprises adding a feature of the weighted signals together or calculating a mean of a feature of the weighted signals;

- the method and system further comprise, prior to combining the weighted signals, evaluating electromyographic quality of the weighted signals;

- evaluating electromyographic quality comprises applying to the weighted signals quality indexes for detection of at least one of the following parameters:

- signal-to-noise ratio;
- maximum-to-minimum drop in power density;
- power spectrum deformation;
- electrical activity related to electrocardiogram/esophageal peristalsis;

- evaluating electromyographic quality comprises adding to each other two of the weighted signals detected through respective electrodes situated on opposite sides of the center of the electrically active region to produce a corresponding addition signal, subtracting these two weighted signals from each other to produce a corresponding subtraction signal, and comparing these addition and substration signals, this comparison being representative of the electromyographic quality of the weighted signals;

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- the method and system further comprise, prior to combining the weighted signals, replacing the weighted signals whose evaluated quality is insufficient; and

5   - the method and system comprise replacing the weighted signals whose evaluated quality is insufficient either by predicted values or by a last value of the weighted signals considered as containing electromyographic information; and

10   - the method and system comprise replacing the higher quality electromyographic signal in response to weighted signals of insufficient quality.

The objects, advantages and other features of the present
15 invention will become more apparent upon reading of the following non restrictive description of a preferred embodiment thereof, given by way of example only with reference to the accompanying drawings.

20   BRIEF DESCRIPTION OF THE DRAWINGS

In the appended drawings:

25   Figure 1 is a schematic representation of a set-up of an EMG analysis system;

Figure 2 is a section of oesophageal catheter on which an array of electrodes of the EMG analysis system of Figure 1 is mounted;
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Figure 3 is a graph showing a set of EMG signals of the diaphragm (EMGdi signals) detected by pairs of successive electrodes of the array of Figure 2;

5   Figure 4 is a flow chart illustrating the operation of a preferred embodiment of the method and system according to the invention, for producing a higher quality electromyographic signal describing the myoelectrical activity of a muscle;

10   Figure 5 is a graph showing the distribution of correlation coefficients calculated for determining the position of the center of an electrically active region (EARdi center) of the diaphragm of a subject along the array of electrodes of Figure 2;

15   Figure 6 is a schematic diagram illustrating the concept embodied by the method and system according to the present invention;

Figure 7 illustrates an exemplary weighting function related to the EMGdi signals collected through the array of electrodes of Figure 2;

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Figure 8a is a first graph showing the gain values of a weighting function $W(n)$ associated with the various pairs of electrodes of the array, when the center of the electrode array symmetrically overlies the EARdi center and the EARdi center is centered between a pair of electrodes;

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Figure 8b is a second graph showing the gain values of a weighting function $W(n)$ associated with the various pairs of electrodes of the array, when the center of the electrode pair is shifted with respect to the EARdi center by a distance smaller than 0.5 inter-electrode distance, and the

30   EARdi center is located between the electrodes of the central pair of the electrode array;

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Figure 8c is a third graph showing the gain values of a weighting function **W(n)** associated with the various pairs of electrodes of the array, when the center of the array is shifted with respect to the EARdi center by a distance equal to 0.5 inter-electrode distance and the EARdi center overlies an electrode common to both the central electrode pair and another adjacent electrode pair;

Figure 8d is a fourth graph showing the gain values of a weighting function **W(n)** associated with the various pairs of electrodes of the array, when the center of the array is shifted with respect to the EARdi center by a distance between 0.5 and 1.5 inter-electrode distance;

Figure 8e is a fifth graph showing the gain values of a weighting function W(n) associated with the various pairs of electrodes of the array, when the center of the array is shifted with respect to the EARdi center but the EARdi center is centered between a pair of electrodes as in Figure 8a, and two missing EMGdi signals are predicted;

Figure 8f is a sixth graph showing the gain values of a weighting function W(n) associated with the various pairs of electrodes of the array, when the center of the array is shifted with respect to the EARdi center by a distance smaller than 0.5 inter-electrode distance as in Figure 8b, the EARdi center is located but not centered between a pair of electrodes, and two missing EMGdi signals are predicted;

Figure 8g is a seventh graph showing the gain values of a weighting function W(n) associated with the various pairs of electrodes of the array, when the center of the array is shifted with respect to the EARdi center, the EARdi center overlies an electrode of the array as in Figure 8c, and two missing EMGdi signals are predicted;

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Figure 9 is a graph showing measured and predicted electrode filtering effects along an array of electrodes such as that shown in Figure 2;

5   Figure 10 is another graph showing measured electrode filtering effects along an array of electrodes comprising overlapping pairs of electrodes;

Figure 11 is a further graph showing measured electrode

10   filtering effects along the array of electrodes of Figure 2 for an inter-electrode distance of 5 mm; and

Figure 12 is still further a graph showing measured electrode filtering effects along the array of electrodes of Figure 2 for an inter-

15   electrode distance of 10 mm.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

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Electromyographic signals produced by a muscle can be detected by means of an array of electrodes passing through the center of the muscle electrically active region. The EMG signals detected through the electrodes comprise electromyographic and noise components, and the

25   position of the center of the electrically active region of the muscle can be detected through a reversal of polarity of the electromyographic components of the electrode-sensed EMG signals provided that the polarity of the electrode pairs is consistent from one end to the other of the electrode array.

30   Although the preferred embodiment of the present invention will be described in relation to an electromyographic signal produced by the

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diaphragm of a subject, it should be kept in mind that it is within the scope of the present invention to process a signal representative of the myoelectrical activity of a muscle other than the diaphragm.

5   According to the preferred embodiment of the present invention, myoelectrical activity of the diaphragm 11 of a human subject 14 is measured through an array of electrodes such as 12 (Figures 1 and 2) mounted on the free end section 15 of an oesophageal catheter 13. As better illustrated in Figure 2, the electrodes 12 are separated by an inter-electrode 10   distance **d**.   Figure 1 shows that the catheter 13 is introduced into the subject's oesophagus through one nostril or the mouth until the array of electrodes 12 is situated at the level of the gastroesophageal junction.

        An electrode 12 can be mounted on the free end section 15   15 of the catheter 13 by winding stainless steel wire (not shown) around that catheter 13.   The wound stainless steel wire presents a rough surface smoothed out by solder, which in turn is electroplated with nickel, copper and then gold or silver. Of course, it is within the scope of the present invention to use other electrode structures. Also, the electrodes 12 can possibly be 20   applied to a nasogastric feeding tube (not shown) which is routinely introduced in intensive-care unit (ICU) patients.

        Electric wires (not shown) interconnect each pair of successive electrodes such as 1-7 (Figure 2) with a respective one of a group 25   of differential amplifiers 16. Obviously, these electric wires follow the catheter 13 from the respective electrodes 12 to the corresponding amplifiers 16, and are preferably integrated to the catheter 13. Preferably, the electric wires transmitting the EMGdi signals (EMG signals from the diaghragm) collected by the various pairs 1-7 of electrodes 12 are shielded to reduce the influence 30   of external noise, in particular disturbance from the 50 or 60 Hz current and voltage of the elecric mains.

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The group of differential amplifiers 16 amplifies and band-pass filters each EMGdi signal. This subtraction step can also be carried out in the personal computer 19 when the amplifiers 16 are single-ended or equivalently designed amplifiers (monopolar readings).

In the example illustrated in Figures 1 and 2, the free end section 15 of the catheter 13 is provided with an array of eight electrodes 12 defining seven pairs 1, 2, 3, 4, 5, 6 and 7 of successive electrodes 12 respectively collecting seven different EMGdi signals. Although it has been found that myoelectrical activity of the diaphragm can be measured accurately with an oesophageal catheter 13 provided on the free end section 15 thereof with an array of eight electrodes 12, a different number and/or configuration of pairs of electrodes 12 can be contemplated depending on the subject's anatomy and movement of the diaphragm. Also, the pairs 1-7 do not need to be pairs of successive electrodes; they can be overlapping pairs of electrodes or can present any other configuration of electrode pairs.

A major problem in recording EMGdi signals is to maintain the noise level as low and as constant as possible. Since the electric wires transmitting the EMGdi signals from the electrodes 12 to the differential amplifiers 16 act as an antenna, it is crucial, as indicated in the foregoing description, to shield these electric wires to thereby protect the EMGdi signals from additional artifactual noise. Also, the package enclosing the differential amplifiers 16 is preferably made as small as possible (miniaturized) and is positioned in close proximity to the subject's nose to decrease as much as possible the distance between the electrodes 12 and the amplifiers 16.

The amplified EMGdi signals are sampled by a personal computer 19 through respective isolation amplifiers of a unit 18, to form signal segments of fixed duration. Unit 18 supplies electric power to the various electronic components of the differential and isolation amplifiers while

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ensuring adequate isolation of the subject's body from such power supply. The unit 18 also incorporates bandpass filters included in the respective EMGdi signal channels to eliminate the effects of aliasing. The successive EMGdi signal segments are then digitally processed into the personal

5   computer 19 after analog-to-digital conversion thereof. This analog-to-digital conversion is conveniently carried out by an analog-to-digital converter implemented in the personal computer 19. The personal computer 19 includes a monitor 40 and a keyboard 31.

10   It is believed to be within the capacity of those of ordinary skill in the art to construct suitable differential amplifiers 16 and an adequate isolation amplifiers and power supply unit 18. Accordingly, the amplifiers 16 and the unit 18 will not be further described in the present specification.

15   An example of the seven EMGdi signals collected by the pairs 1-7 of successive electrodes 12 (Figures 1 and 2) and supplied to the computer 19 is illustrated in Figure 3.

Step 401:

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The first operation (step 401 of Figure 4) performed by the computer 19 is a filtering operation to remove from all the EMGdi signals of Figure 3 electrode motion artifacts, cardiac activity, electrical activity related to esophageal peristalsis, 50 and 60 Hz interference from the electric network,

25   and high frequency noise. Implementation of such filtering is believed to be within the capacity of those of ordinary skill in the art and, accordingly, will not be further described.

Steps 402 and 403:

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As the diaphragm is generally perpendicular to the longitudinal axis of the oesophageal catheter 13 equipped with an array of electrodes 12, only a portion of the electrodes 12 are situated in the vicinity of the diaphragm. It is therefore important to determine the position of the

5   diaphragm with respect to the oesophageal electrode array. Also, the diaphragm moves during breathing and the method and system according to the invention accounts for this movement of the diaphragm.

The portion of the crural diaphragm 11 which forms the

10   muscular tunnel through which the oesophageal catheter 13 is passed is referred to the "diaphragm electrically active region" (EARdi). The thickness of the EARdi is 20-30 mm. It can be assumed that, within the EARdi, the distribution of active muscle fibers has a center from which the majority of the EMGdi signals originate, i.e. the "diaphragm electrically active region center"

15   (EARdi center). Therefore, when the polarity of the recordings is consistent from one end of the electrode array to the other, EMGdi signals detected on opposite sides of the EARdi center will be reversed in polarity with no phase shift; in other words, EMGdi signals obtained along the electrode array become reversed in polarity at the EARdi center.

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Moving centrally from the boundaries of the EARdi, EMGdi power spectrums progressively attenuate and enhance in frequency. Reversal of signal polarity on either side of the electrode pair 4 with the most attenuated power spectrum confirms the position from which the EMGdi

25   signals originate, the EARdi center.

Referring to Figure 4, another function of the computer 19 is to determine the position of the EARdi center along the array of electrodes 12. The EARdi center is repeatedly updated, that is re-determined at

30   predetermined time intervals.

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For that purpose, the EMGdi signals are cross-correlated in pairs in step 402 to calculate cross-correlation coefficients r in step 403. As well known to those of ordinary skill in the art, cross-correlation is a statistical determination of the phase relationship between two signals and

5   essentially calculates the similarity between two signals in terms of a correlation coefficient r. A negative correlation coefficient r indicates that the cross-correlated signals are of opposite polarities.

Figure 5 shows curves of the value of the correlation

10   coefficient r versus the midpoint between the pairs of electrodes from which the correlated EMGdi signals originate. In this example, the inter-electrode distance is 10 mm. Curves are drawn for distances between the correlated pairs of electrodes 12 of 5 mm (curve 20), 10 mm (curve 21), 15 mm (curve 22) and 20 mm (curve 23). One can appreciate from Figure 5 that negative

15   correlation coefficients r are obtained when EMGdi signals from respective electrode pairs situated on opposite sides of the electrode pair 4 are cross-correlated. It therefore appears that the change in polarity occurs in the region of electrode pair 4, which is confirmed by the curves of Figure 3. Accordingly, it can be assumed that the EARdi center is situated substantially

20   midway between the electrodes 12 forming pair 4.

Step 404:

In step 404, the correlation coefficients are systematically

25   compared to determine the EARdi center. For example, the EARdi center can be precisely determined by interpolation using a square law based fit of the three most negative correlation coefficients of curve 21 obtained by successive cross-correlation of the EMGdi signal segments from each electrode pair to the EMGdi signal segments from the second next electrode

30   pair. The EARdi center is associated to a pair of electrodes 12 to provide a

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"reference position".   In the illustrated example, the EARdi center is associated to pair 4 of electrodes 12.

As mentioned in the foregoing description, the position of

5   the EARdi center along the array of electrodes 12 is continuously updated, i.e. re-calculated at predetermined time intervals overlapping or not.

Step 405:

10   Each EMGdi signal obtained on either side of the EARdi center is processed, more specifically multiplied/divided/added/subtracted by a weighting function.   More specifically, a given parameter of the EMGdi signal is multiplied/divided/added/subtracted by the weighting function. This given parameter may comprise a feature such as, for example, an amplitude,

15   power, area under the rectified signal, etc.

The weighting function can be derived from a mathematical model capable of adjusting each EMGdi signal in relation to the relative position of the array of electrodes 12 with respect to the EARdi center. The weighting

20   function can also be obtained from weighting-function-describing data measured on the subject's body, for example by measuring EMGdi signals along the electrode array with knowledge of the position of the EARdi center. Finally the weighting function can be derived from both the mathematical model and the weighting function describing data measured on the subject's

25   body. Also, the processing can be performed in the time domain or in the frequency domain.

The weighting function contains correction for:

30   -   the relative location of the EARdi center with respect to the pairs of electrodes through which the EMGdi signals are obtained;

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- the distance separating the EARdi center from the electrodes;

- the size of the electrically active region (EARdi) of the diaphragm;
and

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- the inter-electrode distance.

Knowing the position of the center of the electrically active
region of the diaphragm (EARdi) about the array or electrodes, the
10 mathematical model can produce weighting functions correcting for both
cancellation effects and distance damping effects.

For the purpose of illustrating this concept, let's consider
Figure 6 in which wanted signals **S** from a wanted signal source 601 and
15 disturbance signals **D** from disturbances 602 are detected through an array
of electrodes 603. The array of electrodes comprises **N** electrodes labeled
n, where **n** = 1, 2, 3, 4 ... **N**. The array of electrodes does not have to be
linearly arranged; any configuration is possible.

20   The signal detected through a given electrode **n** depends
on 1st) the properties of the sources 601 and 602 (point sources or line
sources with particular direction or curved line sources) and 2nd) the distances
$r_s(n)$ and $r_d(n)$, respectively, between the sources 601 and 602 and the
electrode **n**. Line source signals display a mixed frequency and distance
25 dependent damping essentially described by modified bessel functions while
point source signals are damped inversely proportional to the distance and
independent of frequency.

The signal from each electrode is processed through the
30 weighting function **W(n)**, which is a weighting filter which may be positive,

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negative or even equal to zero prior to a summation of all contributions (**n** = 1 to **N**) to give the output signal.

The following relations describe signal conditioning in the spectral domain:

the signal **u(n)** at the given electrode **n** is

$$u(n) = S\ f_s[r_s(n)] + D\ f_d[r_d(n)] \qquad (1)$$

the output signal **Out** 604 is:

$$Out = \sum_{n=1}^{N} u(n)\ W(n) \qquad (2)$$

Combining the two equations and rearranging the terms give the following expression:

$$Out = S \sum_{n=1}^{N} f_s[r_s(n)]\ W(n) + D \sum_{n=1}^{N} f_d[r_d(n)]\ W(n) \qquad (3)$$

where f_s and f_d are functions describing damping and/or other alteration (such as interference) to the signal as a function of distances r_s and r_d, respectively.

Figure 7 is a graph illustrating an example of weighting function **W(n)**. As can be seen the graph of Figure 7 relates the weighting function **W(n)** to the position of the pairs of electrodes from which the EMGdi signals of Figure 3 originate, and the center of the EARdi determined through the correlation coefficients **r** in steps 402-404.

In Figure 7, curve 701 illustrating the weighting function **W(n)** shows that signals from electrode pairs 1, 2, 3, 4, 5, 6 and 7 are represented by

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respective local gain values of the weighting function **W(n)**. The local gain values for all electrode pairs is determined by the position of the EARdi center along the array of electrodes. More specifically, the local gain value of electrode pair 4 is the gain value of curve 701 determined by the position of

5   the EARdi center itself centered between the electrodes of pair 4 (see dashed line 702). The local gain value of electrode pairs 1, 2, 3, 5, 6 and 7 is the gain value of curve 701 at positions shifted from the EARdi center by a corresponding number of inter-electrode distances (see dashed lines 703-708). In the illustrated example, the signal from electrode pair 1 will be

10   represented by gain value 0.05 (dashed line 703), the signal from electrode pair 2 will be represented by gain value 0.3 (dashed line 704), the signal from electrode pair 3 will be represented by gain value 0.9 (dashed line 705), the signal from electrode pair 4 will be represented by gain value 0.3 (dashed line 702), the signal from electrode pair 5 will be represented by gain value 0.9

15   (dashed line 706), the signal from electrode pair 6 will be represented by gain value 0.3 (dashed line 707), and the signal from electrode pair 7 will be represented by gain value 0.05 (dashed line 708).

         In general terms, for a good performance, the first term of Equation
20   3 should be maximized and the second term minimized, or depending on the application of concern, known filtering strategies should be used to optimize the spectral distributions of wanted and disturbance signals. The optimization is performed by varying sign, strength, and spectral (complex) contents of the weighting filter W(n). This process can be guided by a priori knowledge of the

25   type of signal source (line, point, etc.) and the corresponding type of damping (modified bessel functions, inverse distance damping, etc.) and/or experimental knowledge of the signals spectral content.

         Figures 8a-8c are graphs showing the effect of moving the EARdi
30   center along the array of electrodes from a position in which the EARdi center is located centrally between a pair of electrodes to a position in which the

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EARdi center overlies an electrode. These graphs clearly show how the signal amplitudes along the array of electrodes are affected by alteration of the position of the EARdi center with respect to the electrode pair 4.

5   The graph of Figure 8a shows the gain values of the weighting function **W(n)** associated with the various pairs of electrodes of the array, when the center of the electrode array symmetrically overlies the EARdi center and the EARdi center is centered between the central electrode pair 4. The position of the EARdi center is the same as illustrated in Figure 7. In
10   Figure 8a, electrode filtering is symmetrical and presents cancellation at electrode pair 4.

The graph of Figure 8b illustrates the gain values of a weighting function **W(n)** associated with the various pairs of electrodes of the array,
15   when the center of the array is shifted with respect to the EARdi center by a distance smaller than 0.5 inter-electrode distance. More specifically, in Figure 8b, the EARdi center is moved (upwardly in the figure) by 25% of the inter-electrode distance. In this example, the weighting function is skewed, but there is still some cancellation at electrode pair 4.
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Figure 8c is a third graph showing the gain values of a weighting function **W(n)** associated with the various pairs of electrodes of the array, when the center of the array is shifted with respect to the EARdi center by a distance equal to 0.5 inter-electrode distance and the EARdi center is
25   centered on an electrode. The resulting weighting function is symmetrical with no cancellation at electrode pair 4.

The above Figures 8a, 8b and 8c show three (3) possible locations of the EARdi center relative to an electrode pair centered on the electrode
30   array. The fourth figure, namely Figure 8d, exemplifies the behavior of the signals if the EARdi center continues to move over to an adjacent electrode

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pair. In this latter case, the gain values are the same as in Figure 8b but are reversed.

Figures 8e, 8f and 8g show the same positional shifts as in Figures
5   8a, 8b and 8c but when the EARdi center is located at electrode pair 2 instead of central electrode pair 4. The EMGdi signals corresponding to weighting function gain values **W(n+2)** and **W(n+3)** then fall outside of the electrode array. The missing weighted signals can then be predicted by using the same EMGdi signal detected at electrode pairs 4 and 3 processed through the
10   weighting function. These predicted values are then used in the calculation for the total signal strength across the electrode array.

In this preferred embodiment, the electrodes at the bottom of the array (Figures 8e-g) are not used. However, depending on how complex the
15   model for prediction and computation is, these signals can also be used. If correction for signals that fall off the electrode array is not performed, it is impossible to obtain an accurate estimate of the total signal value.

Just a word to mention that the weighting function **W(n)** of the
20   Figures 7 and 8 regards conditioning of the amplitude of the EMGdi signal and corresponds to curve 901 of Figure 9 (curve of the amplitude of the EMGdi signal in relation to the distance of the electrodes of the pair from the EARdi center). The EMGdi signals can also be frequency conditioned by constructing a weighting filter using a curve such as 902 in Figure 9 (curve of
25   the center frequency of the EMGdi signal in relation to the distance of the electrodes of the pair from the EARdi center). A combination of frequency and amplitude conditioning can also be implemented.

Figures 10, 11 and 12 are other examples of amplitude and
30   frequency conditioning curves that can serve as weighting functions **W(n)**.

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The curves of Figures 9, 10, 11 and 12 are usually experimentally established on a sufficient number of recordings in a subject.

Step 406:

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In this step, electromyographic quality of the weighted signals is evaluated.

This evaluation of the electromyographic quality of all the weighted

10 signals can be performed for their relative electromyographic and noise components. Thus, if preferred, summation of the EMGdi signals (amplitude, area under the curve, power, etc.) along the array of electrodes can be limited to signals that contain physiological information pertaining to the diaphragm. This evaluation of signals content can be performed by applying well known

15 signal quality indexes for detection of signal-to-noise ratio, maximum-to-minimum drop in power density, power spectrum deformation, and/or electrocardiogram/esophageal peristalsis.

This evaluation of signals for their relative electromyographic and

20 noise components can also be obtained by adding and subtracting EMGdi signals obtained on opposite sides with symmetrical position to the electrically active region center (for example signals from electrode pairs 3 and 5 in Figure 7) and comparing the results of these addition and subtraction. A first EMGdi signal detected by a pair of electrodes of the array on a first side of the

25 center of the EARdi has an electromyographic component of a first polarity and a noise component of given polarity. A second EMGdi signal detected by another pair of electrodes of the array on the second side of the EARdi center, opposite to the first side, has an electromyographic component of a second polarity opposite to the first polarity and a noise component of said

30 given polarity. Subtraction of the first and second EMGdi signals subtracts the noise components of the first and second EMGdi signals from each other

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but adds the electromyographic components of these first and second EMGdi signals together to produce a resulting signal with high electromyographic content and low noise content. Addition of the first and second EMGdi signals adds the noise components of the first and second EMGdi signals to each other but subtracts the electromyographic components of these first and second EMGdi signals from each other to produce a signal with low electromyographic content and high noise content. Comparison of the resulting added and subtracted signals (area under the curve/power/amplitude of the signals) provides information about the relative contribution of noise and electromyographic content to the signal. Signals with a high electromyographic content will be considered as a high quality signal.

Step 407:

EMGdi signals considered as not containing physiological information (insufficient quality as determined in step 406) pertaining to the diaphragm can be replaced by predicted values or simply the last value considered to contain physiological information pertaining to the diaphragm. This replacement strategy can be applied on either each single EMGdi signal obtained from the electrode array or on the summation or mean of the weighted EMGdi signals representative for all or some of the signals obtained along the electrode array.

Step 408:

The last step consists of calculating the sum of a feature (RMS voltage, RMS current, power, RMS means amplitude, area under the curve, etc) of the eventually replaced, signal quality evaluated weighted EMGdi signals from the electrodes of the array. A mean of the rectified signals, or a

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RMS or other suitable or equivalent value of these signals can be calculated as well for further use.

The resulting signal will provide improvement of the signal-to-noise ratio and minimize influence of electrode filtering due to changes in the position of the electrode array relative the muscle's electrically active region center. It also accounts for differences in anatomy between individuals and differences in inter-electrode distance and design, and for the EARdi center approaching the distal or proximal end of the array of electrodes.

Of course, the application of the present invention is not limited to the diaphragm but to any other muscle and that, for any type of array of electrodes.

Although the present invention has been described hereinabove by way of a preferred embodiment thereof, this embodiment can be modified at will, within the scope of the appended claims, without departing from the spirit and nature of the subject invention.

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WHAT IS CLAIMED IS:

1.   A method of producing a higher quality
electromyographic signal describing myoelectrical activity of an electrically
active region of a subject's muscle, comprising:

sensing through an array of electrodes a plurality of EMG
signals representative of the myoelectrical activity of the electrically active
region of the subject's muscle;

applying a weighting function to the detected EMG signals
and thereby producing weighted signals, the weighting function containing
correction features for the relative locations of the electrically active region
and the electrodes; and

combining the weighted signals and thereby producing the
higher quality electromyographic signal.

2.   A method of producing a higher quality
electromyographic signal as defined in claim 1, wherein:

the electrically active region of the subject's muscle
comprises a center;

the electrodes are separated from the center of the
electrically active region by respective distances;

the electrodes are separated from each other by an inter-
electrode distance; and

the weighting function comprises correction features for:

    – the relative location of the center of the
electrically active region and the electrodes;

    – the distance separating the center of the
electrically active region and the electrodes;

    – the size of the electrically active region; and

    – the inter-electrode distance.

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3. A method of producing a higher quality electromyographic signal as defined in claim 1, wherein the weighting function comprises correction features for both cancellation and distance damping effects.

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4. A method of producing a higher quality electromyographic signal as defined in claim 1, wherein the electrically active region of the subject's muscle comprises a center, the array of electrodes comprises a series of electrodes with an inter-electrode distance, each EMG signal is detected through at least two electrodes of the array, and wherein applying the weighting function comprises:

detecting the position of the center of the electrically active region about the array of electrodes;

relating the weighting function to the position of the center of the electrically active region with respect to the electrodes of said series;

weighting each EMG signal by means of the weighting function related to the position of the center of the electrically active region with respect to the electrodes of said series.

5. A method of producing a higher quality electromyographic signal as defined in claim 4, wherein the series of electrodes has a center, and wherein, when the center of the electrically active region is offset with respect to the center of the series of electrodes:

a larger number of EMG signals are detected by the electrodes on one side of the center of the electrically active region than on the other side of said center of the electrically active region so that EMG signals are missing on said other side; and

weigthing of the EMG signals comprises replacing the missing EMG signals on said other side by corresponding EMG

signals from said one side and subsequently weighting said replacement EMG signals.

5   6.   A method of producing a higher quality electromyographic signal as defined in claim 1, wherein combining the weighted signals comprises:

adding a feature of the weighted signals together.

10   7.   A method of producing a higher quality electromyographic signal as defined in claim 1, wherein combining the weighted signals comprises;

calculating a mean of a feature of the weighted signals.

15   8.   A method of producing a higher quality electromyographic signal as defined in claim 1, further comprising, prior to combining the weighted signals, evaluating electromyographic quality of the weighted signals.

20   9.   A method of producing a higher quality electromyographic signal as recited in claim 8, wherein evaluating electromyographic quality comprises applying to the weighted signals quality indexes for detection of at least one of the following parameters:

- signal-to-noise ratio;
25   - maximum-to-minimum drop in power density;
- power spectrum deformation;
- electrical activity related to electrocardiogram/esophageal peristalsis.

30   10.   A method of producing a higher quality electromyographic signal as recited in claim 8, wherein the electrically active

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region of the subject's muscle comprises a center, and wherein evaluating electromyographic quality comprises adding to each other two of the weighted signals detected through respective electrodes situated on opposite sides of the center of the electrically active region to produce a corresponding addition

5   signal, subtracting said two weighted signals from each other to produce a corresponding subtraction signal, and comparing said addition and substration signals, said comparision being representative of the electromyographic quality of the weighted signals.   .

10   11.   A   method   of   producing   a   higher   quality electromyographic signal as recited in claim 8, further comprising, prior to combining the weighted signals, replacing the weighted signals whose evaluated quality is insufficient.

15   12.   A   method   of   producing   a   higher   quality electromyographic signal as recited in claim 11, comprising replacing the weighted signals whose evaluated quality is insufficient by predicted values.

              13.   A   method   of   producing   a   higher   quality
20   electromyographic signal as recited in claim 11, comprising replacing the weighted signals whose evaluated quality is insufficient by a last value of said weighted signals considered as containing electromyographic information.

              14.   A   method   of   producing   a   higher   quality
25   electromyographic signal as recited in claim 8, comprising replacing the higher quality electromyographic signal in response to weighted signals of insufficient quality.

              15.   A   system   for   producing   a   higher   quality
30   electromyographic signal describing myoelectrical activity of an electrically active region of a subject's muscle, comprising:

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an array of electrodes for sensing a plurality of EMG signals representative of the myoelectrical activity of the electrically active region of the subject's muscle;

a weighting filter applied to the detected EMG signals to produce weighted signals, the weighting filter containing correction features for the relative locations of the electrically active region and the electrodes; and

a combiner of the weighted signals, the combined weighted signals constituting the higher quality electromyographic signal.

16.   A system for producing a higher quality electromyographic signal as defined in claim 15, wherein:

the electrically active region of the subject's muscle comprises a center;

the electrodes are separated from the center of the electrically active region by respective distances;

the electrodes are separated from each other by an inter-electrode distance; and

the weighting filter comprises correction features for:

– the relative location of the center of the electrically active region and the electrodes;

– the distance separating the center of the electrically active region and the electrodes;

– the size of the electrically active region; and

– the inter-electrode distance.

17. A system for producing a higher quality electromyographic signal as defined in claim 15, wherein the weighting filter comprises correction features for both cancellation and distance damping effects.

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18.   A system for producing a higher quality electromyographic signal as defined in claim 15, wherein:

the electrically active region of the subject's muscle comprises a center;

5   the array of electrodes comprises a series of electrodes with an inter-electrode distance;

each EMG signal is detected through at least two electrodes of the array; and

the weighting filter comprises a weighting function related
10   to the position of the center of the electrically active region with respect to the electrodes of said series.

19.   A system for producing a higher quality electromyographic signal as defined in claim 15, wherein the series of
15   electrodes has a center, and wherein, when the center of the electrically active region is offset with respect to the center of the series of electrodes:

a larger number of EMG signals are detected by the electrodes on one side of the center of the electrically active region than on the other side of said center of the electrically active region so
20   that EMG signals are missing on said other side; and

the system comprises means for replacing the missing EMG signals on said other side by corresponding EMG signals from said one side, and means for subsequently weighting said replacement EMG signals.

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20.   A system for producing a higher quality electromyographic signal as defined in claim 15, wherein the combiner comprises:

an adder of a feature of the weighted signals.

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21.   A system for producing a higher quality electromyographic signal as defined in claim 15, wherein the combiner comprises:

a calculator of a mean of a feature of the weighted signals.

22.   A system for producing a higher quality electromyographic signal as defined in claim 15, further comprising, prior to combining the weighted signals, an evaluator of an electromyographic quality of the weighted signals.

23.   A system for producing a higher quality electromyographic signal as recited in claim 22, wherein the evaluator comprises means for applying to the weighted signals quality indexes for detection of at least one of the following parameters:

- signal-to-noise ratio;
- maximum-to-minimum drop in power density;
- power spectrum deformation;
- electrical activity related to electrocardiogram/esophageal peristalsis.

24.   A system for producing a higher quality electromyographic signal as recited in claim 22, wherein the electrically active region of the subject's muscle comprises a center, and wherein the evaluator comprises an adder of two of the weighted signals detected through respective electrodes situated on opposite sides of the center of the electrically active region to produce a corresponding addition signal, a subtractor of said two weighted signals from each other to produce a corresponding subtraction signal, and a comparator of said addition and substration signals, this comparision being representative of the electromyographic quality of the weighted signals.

25.   A system for producing a higher quality electromyographic signal as recited in claim 22, further comprising means for replacing, prior to combining the weighted signals, the weighted signals whose evaluated quality is insufficient.

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26.   A system for producing a higher quality electromyographic signal as recited in claim 25, comprising means for replacing the weighted signals whose evaluated quality is insufficient by predicted values.

10

27.   A system for producing a higher quality electromyographic signal as recited in claim 25, comprising means for replacing the weighted signals whose evaluated quality is insufficient by a last value of said weighted signals considered as containing electromyographic

15   information.

28.   A system for producing a higher quality electromyographic signal as recited in claim 22, comprising means for replacing the higher quality electromyographic signal in response to weighted

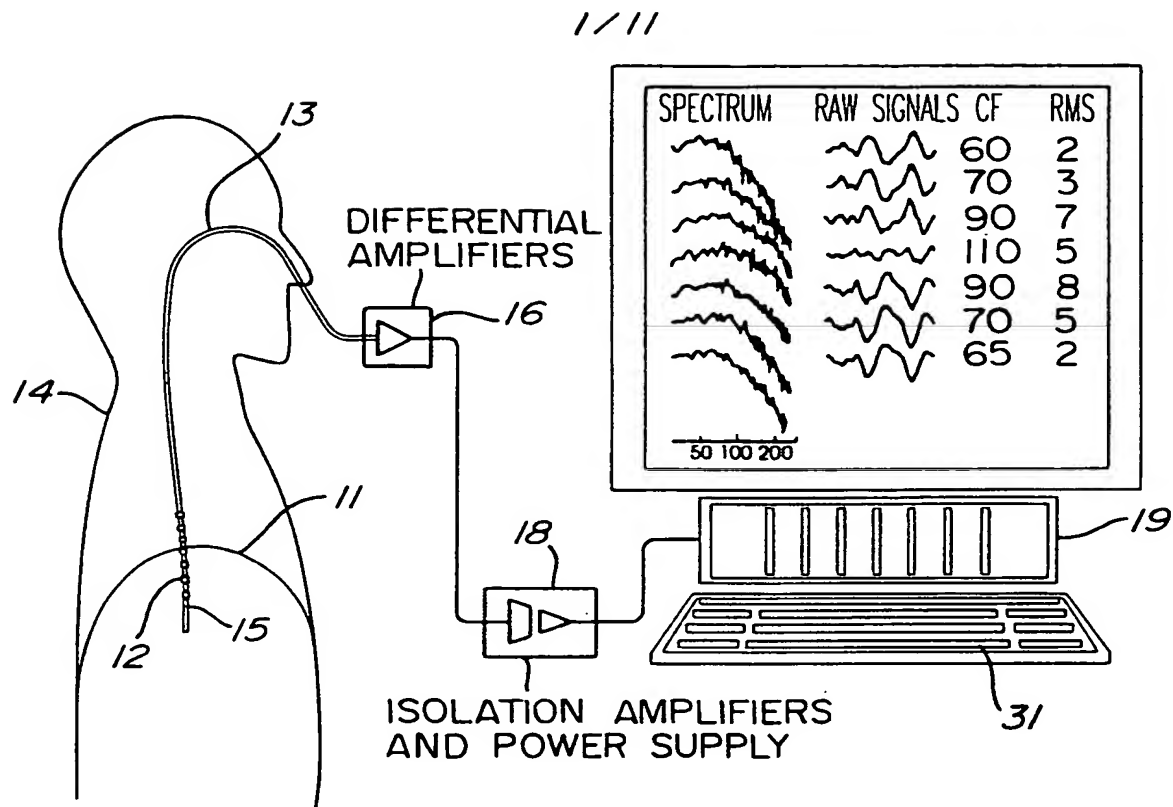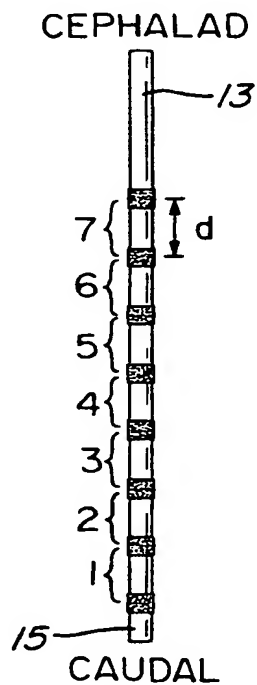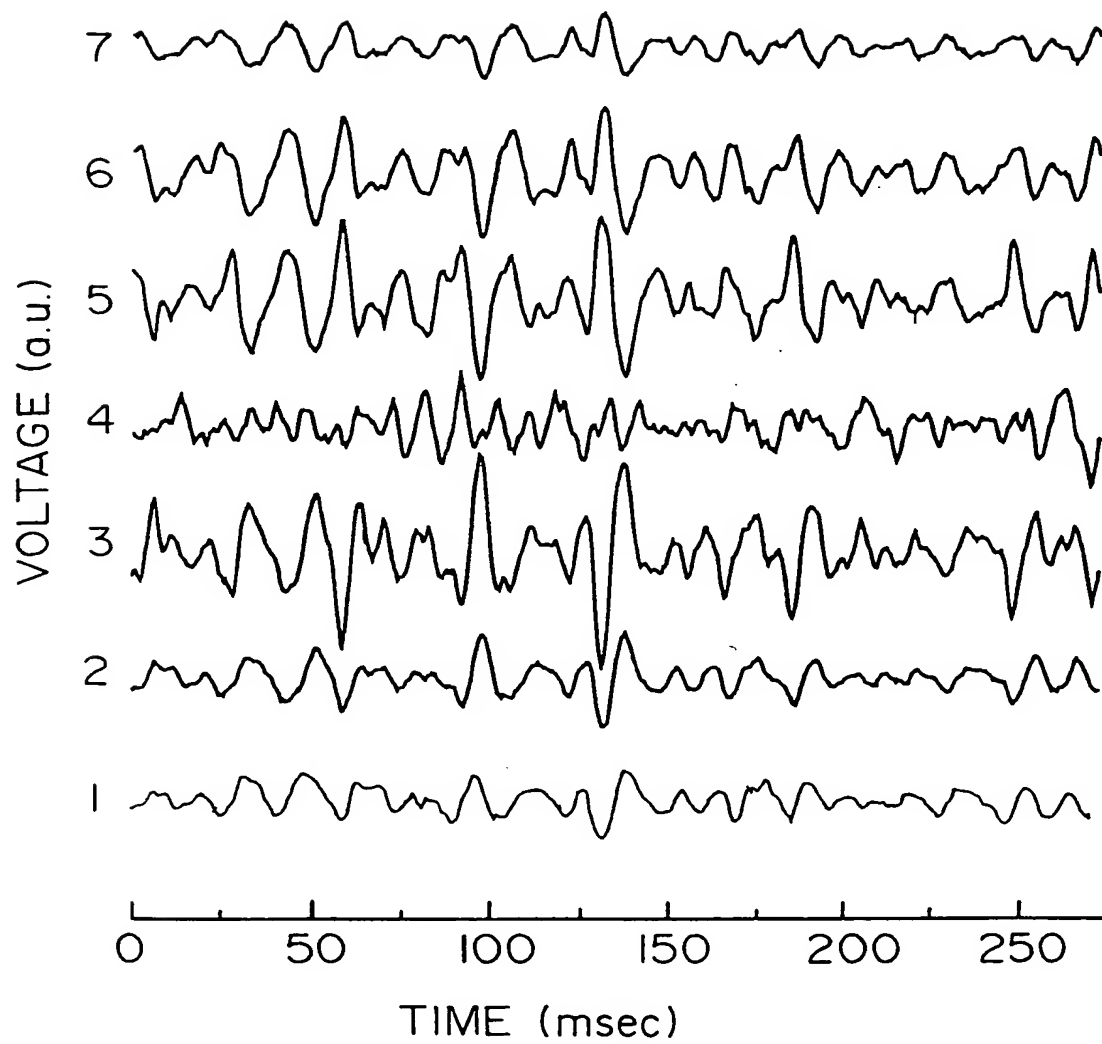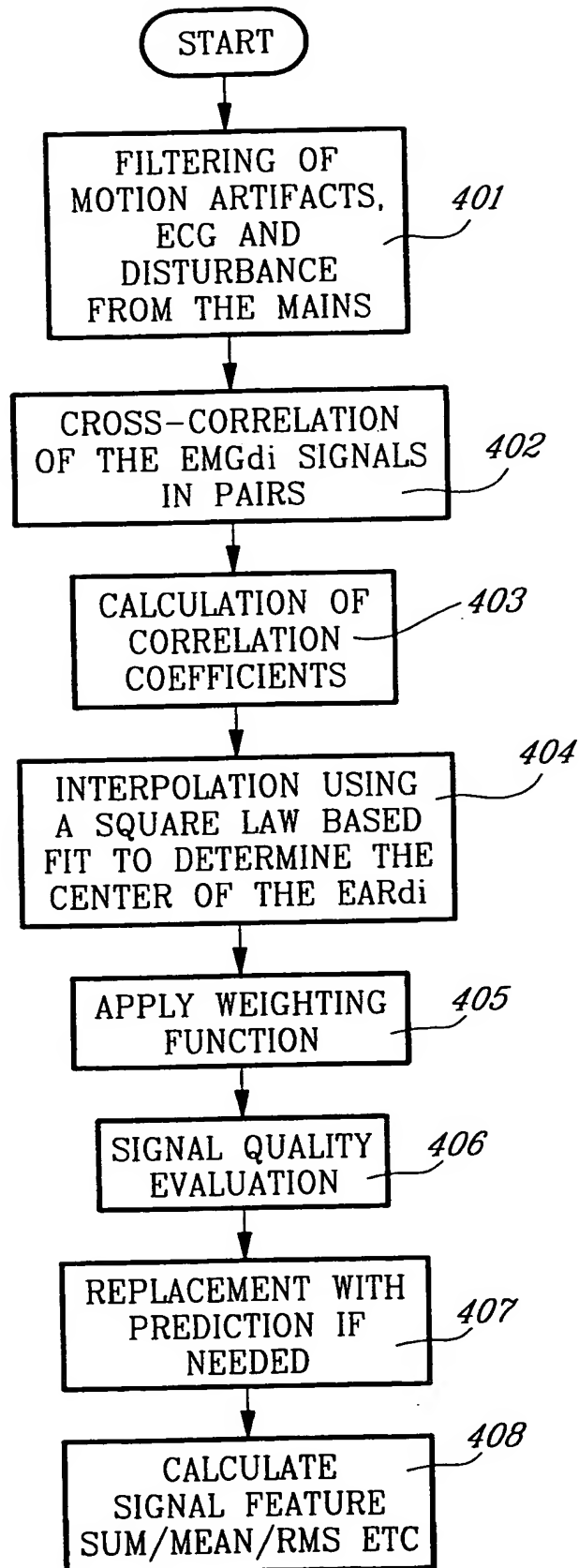20   signals of insufficient quality.

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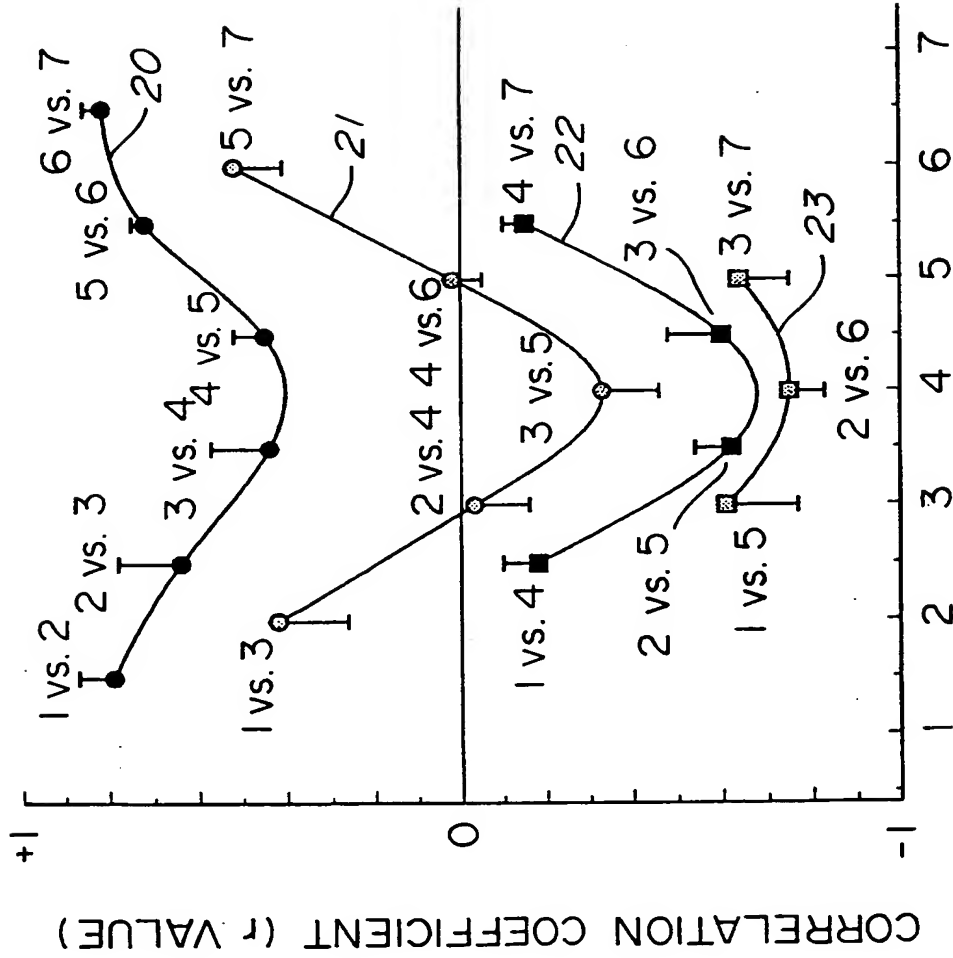
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SPECTRUM	RAW SIGNALS	CF	RMS
		60	2
		70	3
		90	7
		110	5
		90	8
		70	5
		65	2

50 100 200

DIFFERENTIAL AMPLIFIERS

ISOLATION AMPLIFIERS AND POWER SUPPLY

_FIE_1

CEPHALAD

CAUDAL

_FIE_2

FIG_3

3/11

```
                    ┌─────────────┐
                    │    START    │
                    └─────────────┘
                           │
                           ▼
              ┌───────────────────────┐
              │    FILTERING  OF      │
              │  MOTION  ARTIFACTS,   │   401
              │     ECG  AND          │
              │   DISTURBANCE         │
              │  FROM  THE  MAINS     │
              └───────────────────────┘
                           │
                           ▼
              ┌───────────────────────┐
              │   CROSS-CORRELATION   │
              │  OF  THE  EMGdi SIGNALS│   402
              │       IN  PAIRS       │
              └───────────────────────┘
                           │
                           ▼
              ┌───────────────────────┐
              │   CALCULATION  OF     │   403
              │     CORRELATION       │
              │    COEFFICIENTS       │
              └───────────────────────┘
                           │
                           ▼
              ┌───────────────────────┐
              │  INTERPOLATION  USING │   404
              │  A  SQUARE  LAW  BASED │
              │  FIT  TO  DETERMINE  THE│
              │  CENTER  OF  THE  EARdi│
              └───────────────────────┘
                           │
                           ▼
              ┌───────────────────────┐
              │   APPLY  WEIGHTING    │   405
              │      FUNCTION         │
              └───────────────────────┘
                           │
                           ▼
              ┌───────────────────────┐
              │   SIGNAL  QUALITY     │   406
              │     EVALUATION        │
              └───────────────────────┘
                           │
                           ▼
              ┌───────────────────────┐
              │  REPLACEMENT  WITH    │
              │   PREDICTION  IF      │   407
              │      NEEDED           │
              └───────────────────────┘
                           │
                           ▼
              ┌───────────────────────┐
              │     CALCULATE         │   408
              │   SIGNAL  FEATURE     │
              │  SUM/MEAN/RMS  ETC    │
              └───────────────────────┘
```

FIG_4

FIG-5

FIG. 6

FIG. 7

Fig. 8a

Fig. 8b

Fig. 8c

Fig. 8e

Fig. 8d

FIG. 8g

FIG. 8f

FIG. 9

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overlap array (n=5)

FIE-10

5 mm IED array (n=4)

FIE-11

10 mm IED array (n=4)

FIE-12
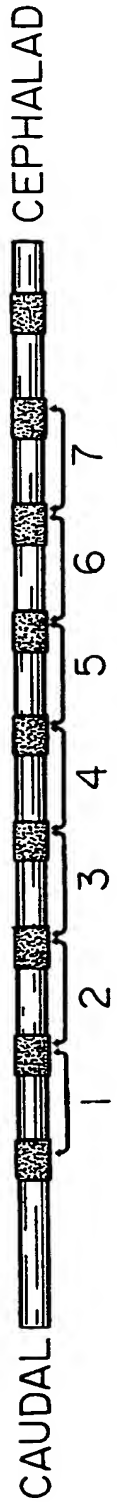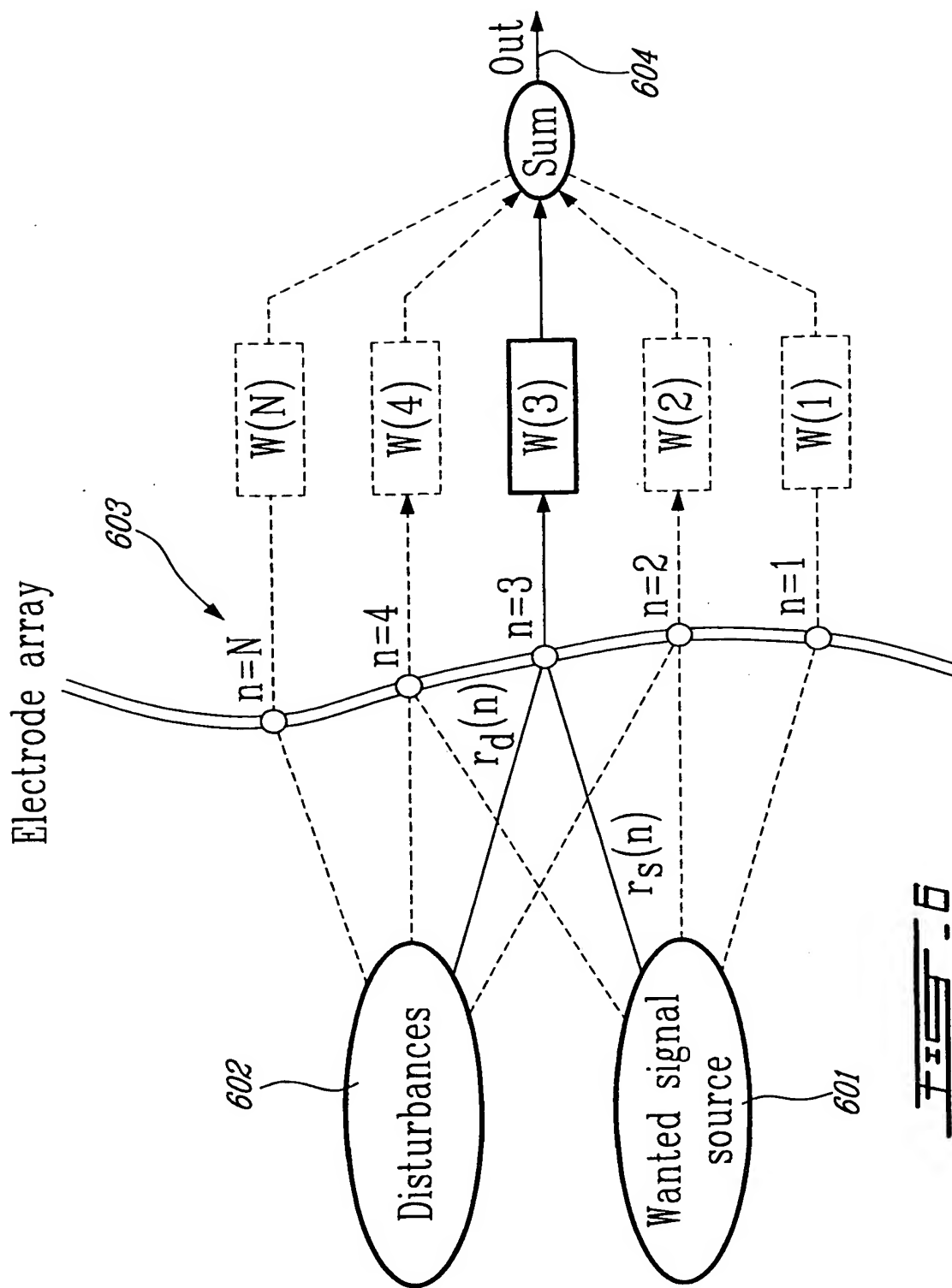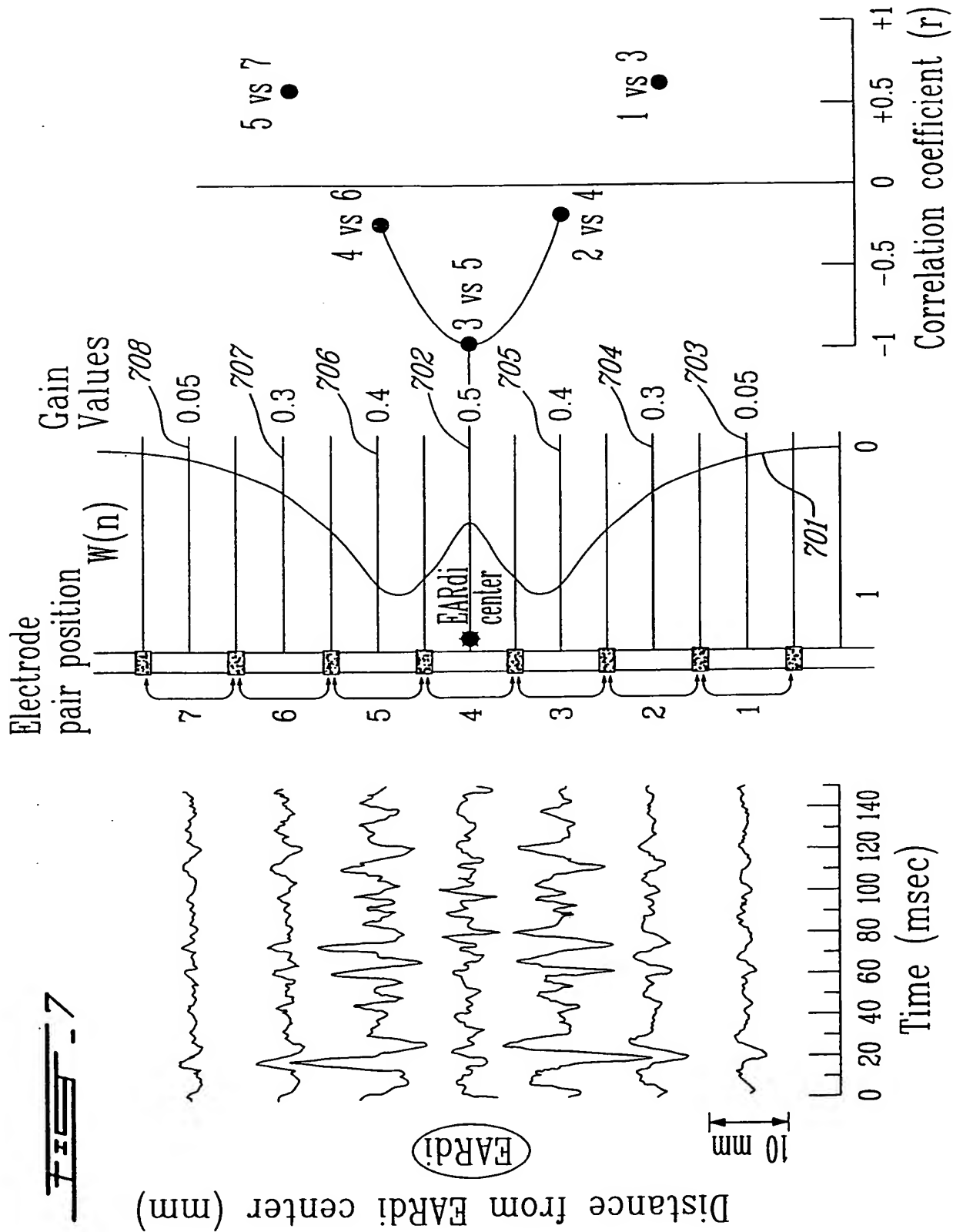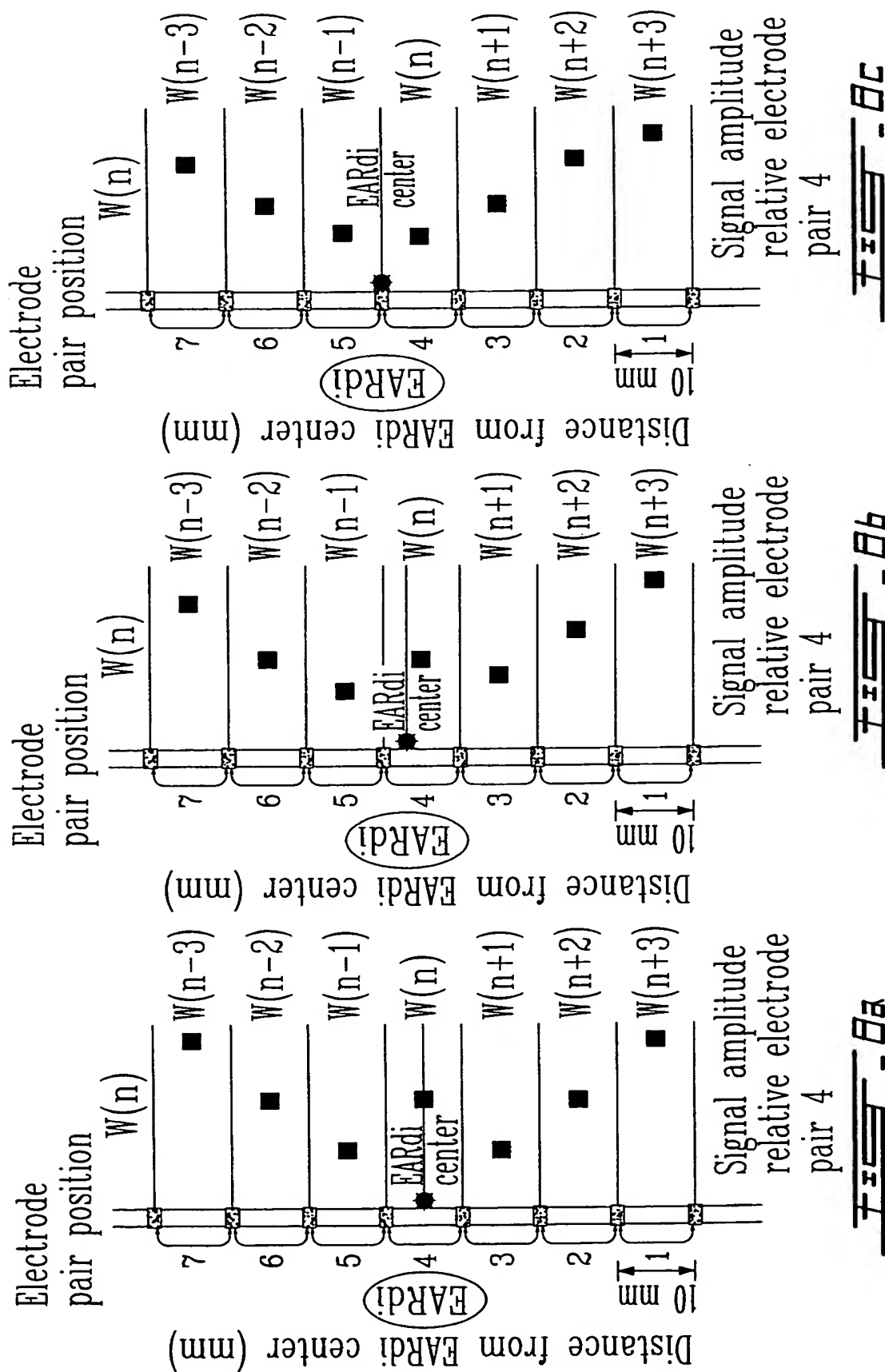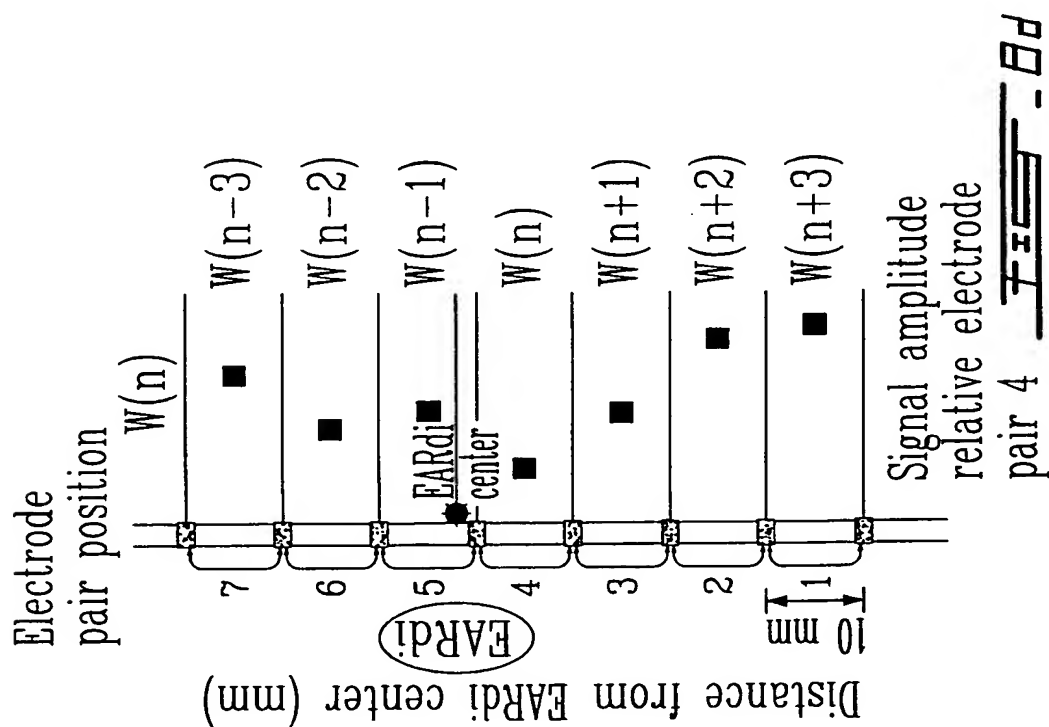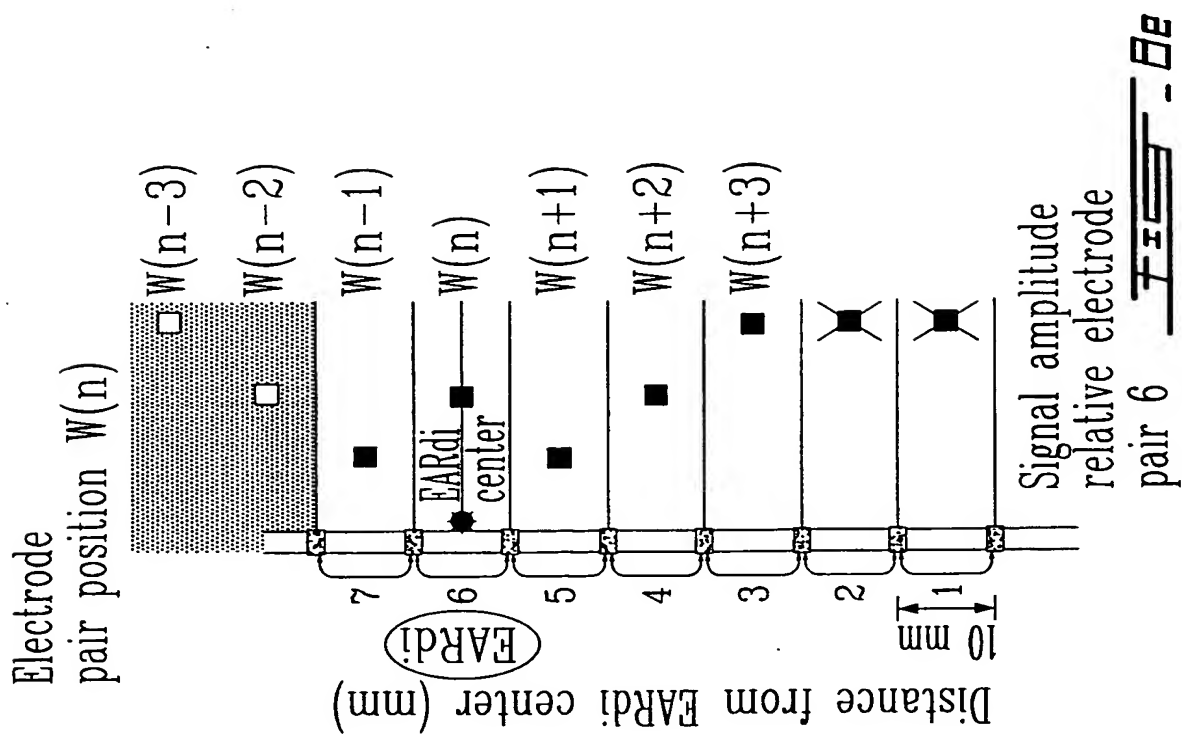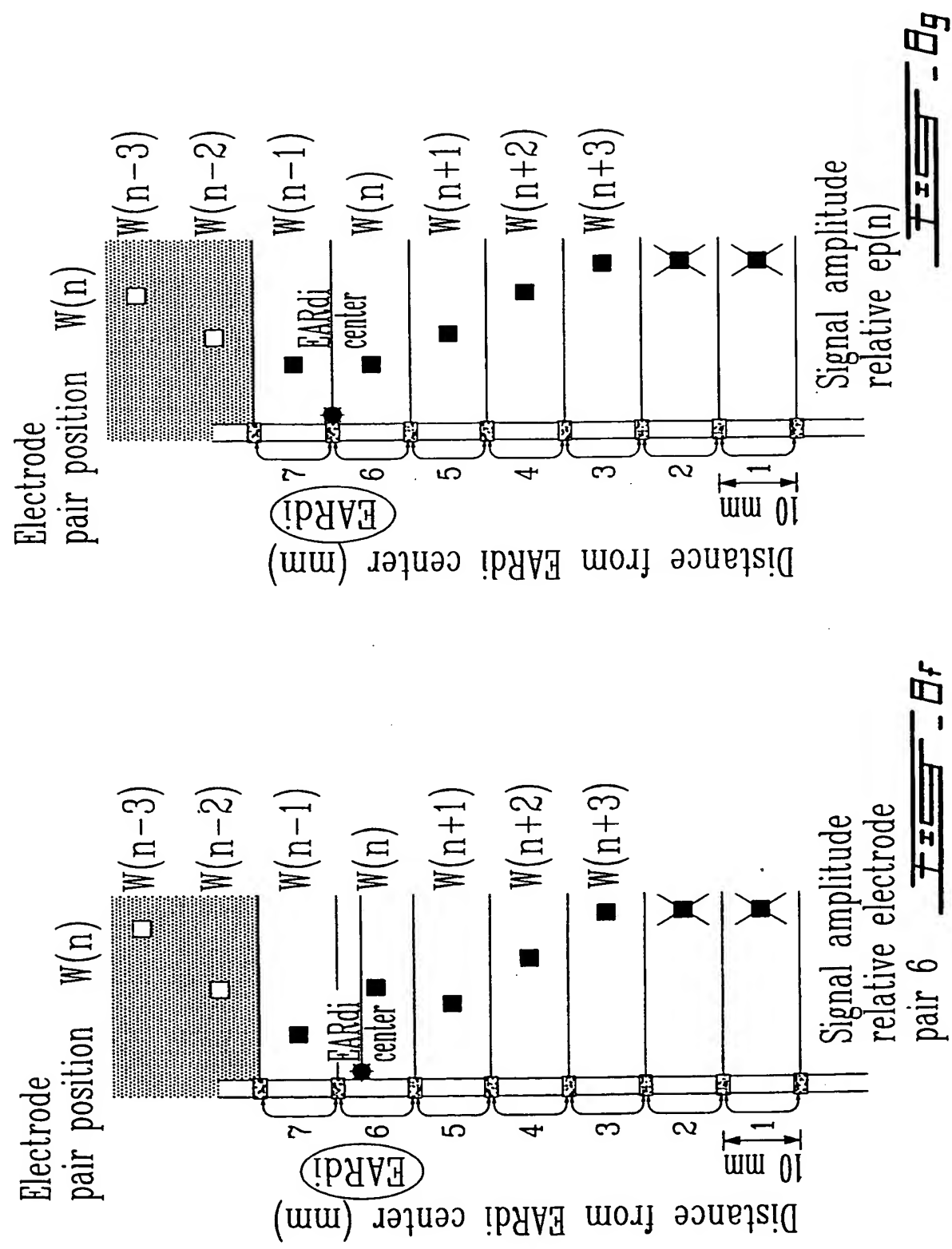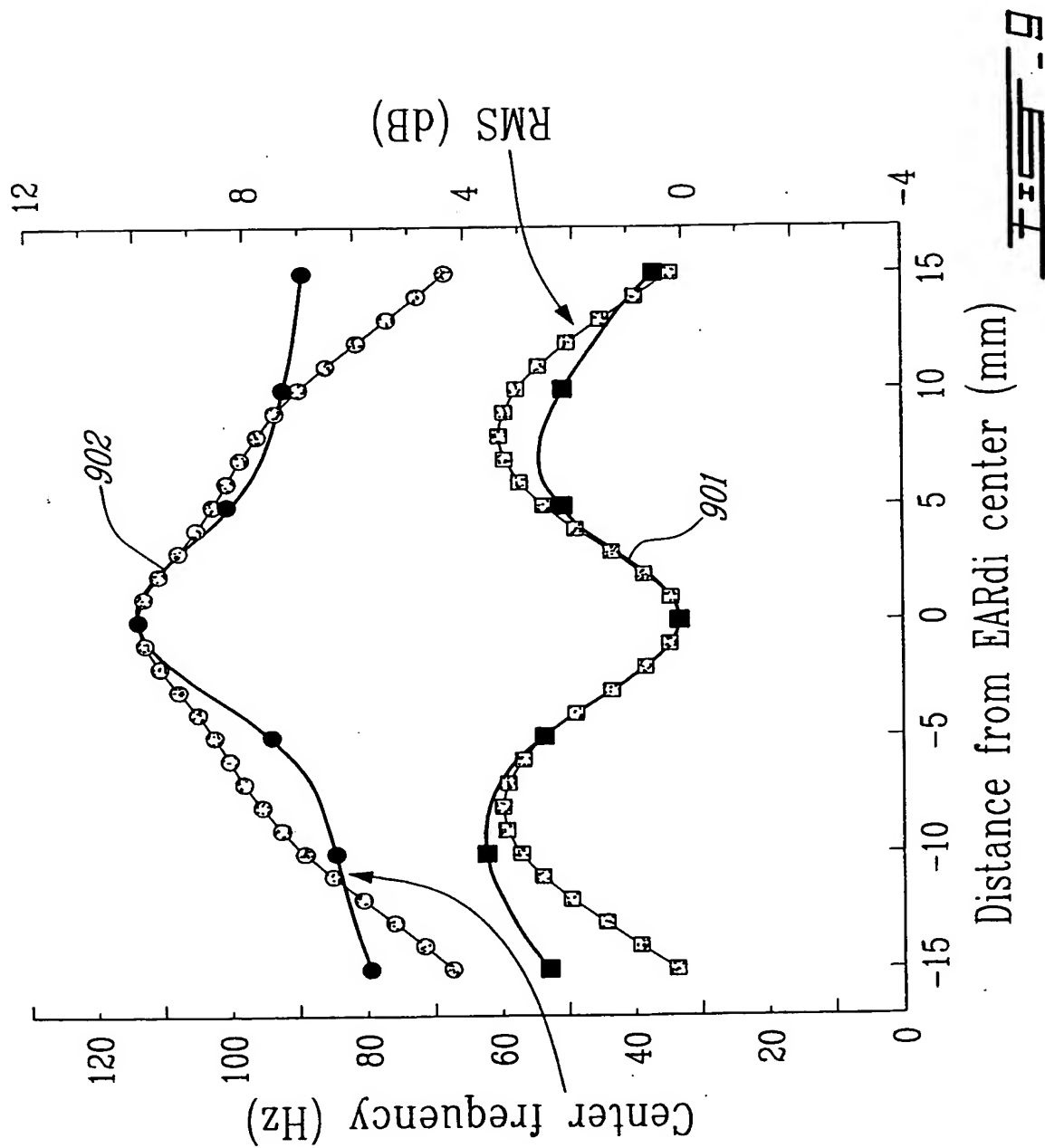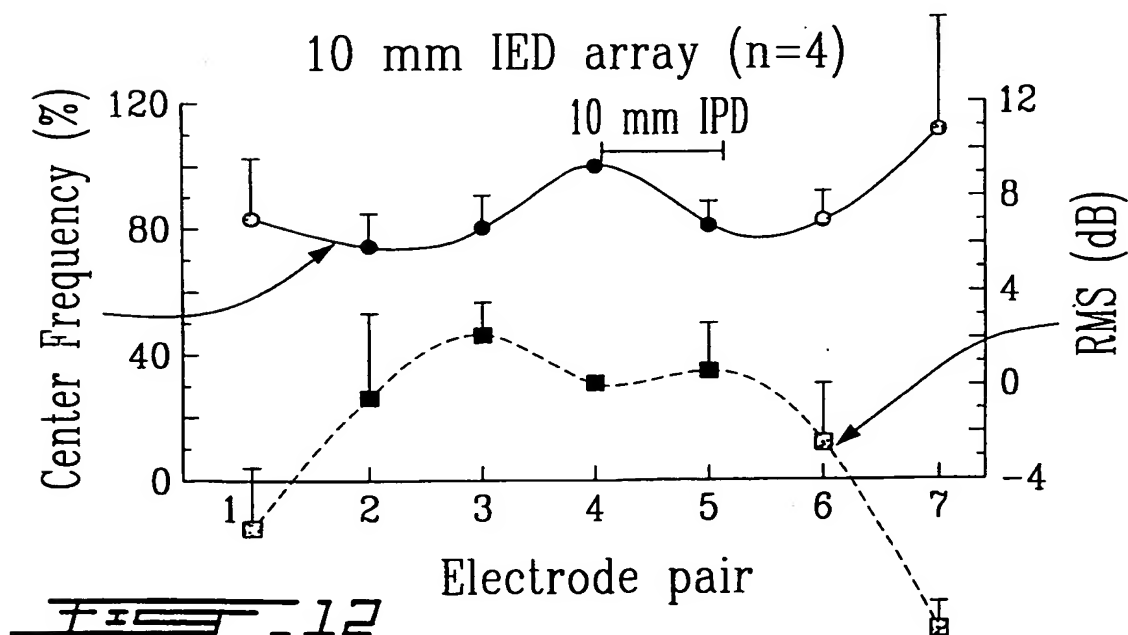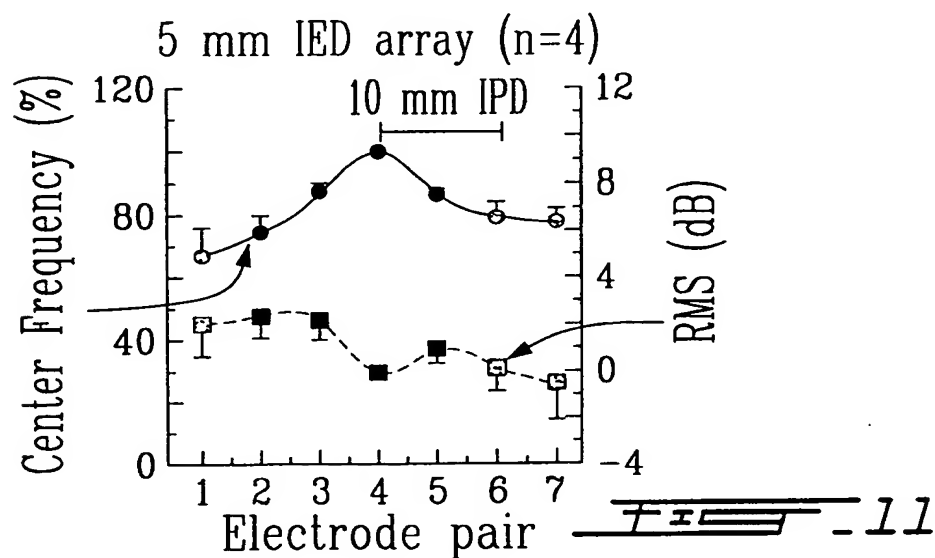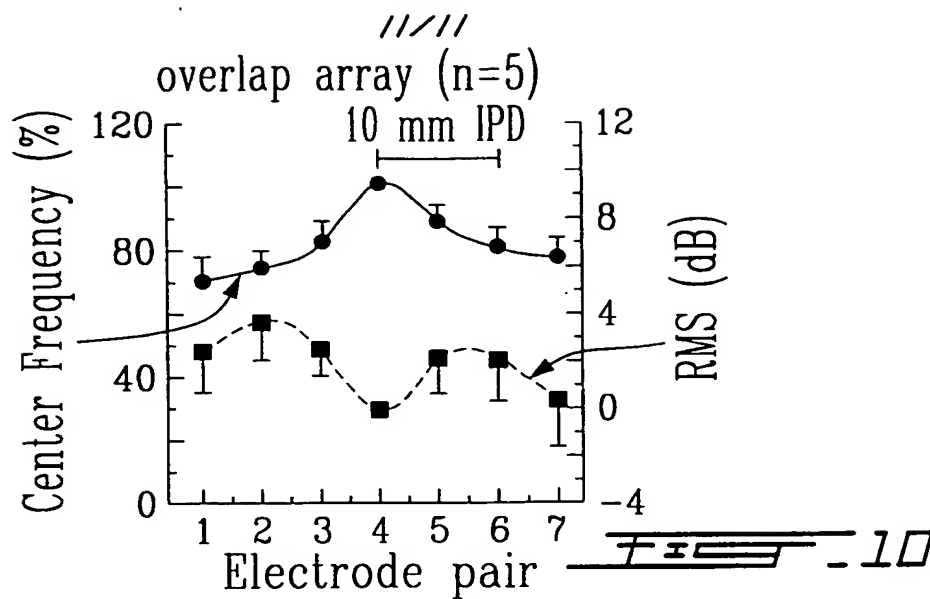
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   A61B5/0488   A61B5/0492

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7   A61B   G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC, BIOSIS, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category°	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	TADASHI MASUDA ET AL: "the position of innervation zones in the biceps brachii investigated by surface electromyography" IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, vol. BME-32, no. 1, 1 January 1985 (1985-01-01), pages 36-42, XP002153958 New York, US page 36, left-hand column, line 1 -page 40, right-hand column, line 28; tables 1-6 ---	1,2,4-8, 10,15, 16, 18-22,24
Y	WO 98 48877 A (GRASSINO ALEJANDRO ;SINDERBY CHRISTER (SE); FRIBERG SVEN (SE); LIN) 5 November 1998 (1998-11-05) page 13, line 19 -page 19, line 14; tables 1-7 ---	1,2,4-8, 10,15, 16, 18-22,24
	-/--	

[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

° Special categories of cited documents :

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Date of the actual completion of the international search	Date of mailing of the international search report
28 November 2000	12/12/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl. Fax: (+31–70) 340–3016	Weihs, J

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category°	Citation of document. with indication.where appropriate. of the relevant passages	Relevant to claim No.
A	US 5 671 752 A (SINDERBY CHRISTER ET AL) 30 September 1997 (1997-09-30) column 2, line 61 -column 5, line 50 ---	1,2,4, 15,16,18
A	HARALD REUCHER ET AL: "spatial filtering of noninvasive emg: part I - introduction to measuring technique and applications" IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, vol. BME-34, no. 2, 1 February 1987 (1987-02-01), pages 98-105, XP002153959 New York, US page 98, column 1, line 1 -page 104, left-hand column, line 2; tables 1-6 -----	1,15

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
WO 9848877	A	05-11-1998	US	5820560 A	13-10-1998
			AU	3534497 A	24-11-1998
			EP	0979118 A	16-02-2000
US 5671752	A	30-09-1997	CA	2172329 A	01-10-1996
			US	5820560 A	13-10-1998